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G. T. Chirima

K. M. Zied

N. Ravirala

K. L. Alderson
University of Bolton, K.Alderson@bolton.ac.uk

Andrew Alderson
University of Bolton, A.Alderson@bolton.ac.uk

Numerical and Analytical Modelling of Multi-layer Adhesive-Film Interface Systems

Gleny T. Chirima, Khaled M. Zied, Naveen Ravirala, Kim L. Alderson, Andrew Alderson‡

Centre for Materials Research and Innovation, University of Bolton, BL3 5AB, UK

Abstract

This paper reports the use of Finite Element Modelling (FEM) simulations of the through-thickness Young's and shear moduli of alternating film-adhesive multi-layer interface materials. The FEM results were compared with analytical modified Rule of Mixtures (RoM) predictions. Two representative adhesives ('low' and 'high' Young's moduli, with respect to the film Young's modulus) were used in combination with both conventional and auxetic films. Enhancements in the Young's modulus and shear modulus of the interface were predicted for the low modulus adhesive systems for both conventional and auxetic films. The auxetic film-low modulus adhesive systems showed enhancements by at least a factor of 2 in the through-thickness mechanical properties compared to the conventional film-low modulus adhesive systems. Of the high modulus adhesive systems, only the auxetic film system showed enhancements in through-thickness mechanical properties. The conventional film-high modulus adhesive systems showed a decrease in the through-thickness Young's and shear moduli.

Keywords**:** Auxetic, negative Poisson's ratio, adhesive, multi-layer interface, FEM

‡Corresponding author: Tel: + (44)1204 903513
Email: A.Alderson@bolton.ac.uk

1. Introduction

Multi-component composite and plastic materials are widely used in various sectors of industry, for example packaging, automotive, aerospace and chemical engineering.[1] Most of these multi-component materials consist of several phases in which an interface exists between the phases.[2] The use of adhesives in the joining of different components is becoming increasingly popular, even for joining two metal components where an adhesive bond is inferior when compared to welded or brazed joints.[3] However, the use of an isotropic resin adhesive alone may not suffice to yield bonded interfaces strong enough to pass rigorous shear, peel and impact resistant tests required in some areas of application. Thus, research advances towards improving the toughness properties of adhesives have resulted in the formulation of multi-phase interfaces in order to improve their mechanical properties.

Although understanding interfacial interactions (chemistry and physics) in multi-component materials is complex, the use of multiphase or multi-component materials is expected to grow with a larger than average rate in the future.[2] Various applications in many areas are envisaged, including nanotechnology, fibre-reinforced composites for structural applications, and barrier properties in flame retardancy.

In this work we have applied analytical and numerical methods to investigate the effect of incorporating thin films of conventional and/or auxetic material within an alternating film-adhesive multi-layer interface system. Auxetic materials possess the fascinating property of expanding transversely under an axial tensile load (i.e. negative Poisson's ratio behaviour). Auxetic materials have been shown to have enhancements in other mechanical properties. By way of demonstration, for isotropic materials shear modulus (G) is related to Young's modulus (E) and Poisson's ratio (ν) by:

$$G = \frac{E}{2(1+\nu)} \quad [1]$$

The thermodynamically allowable range of Poisson's ratio for isotropic materials is

$$-1 \le \nu \le +0.5 \quad [2]$$

As ν approaches -1, the factor $(1+\nu)$ in Eq (1) tends to zero, leading to an extreme enhancement in the shear modulus when compared to a positive Poisson's ratio material of equivalent Young's modulus.

Indentation tests have shown that auxetic foams have considerably higher yield strengths and energy absorption in dynamic impact than conventional foams.[4] The fracture toughness of auxetic foams has been shown to be enhanced by up to 160%, and auxetic foams displayed increased compliance when compared to conventional foams.[5] Auxetic microporous polymers have been shown to have large enhancements in ultrasonic attenuation coefficient; the highest measurable value being 3 times more than conventional materials.[6] Fibre pull-out tests on composites containing auxetic fibres have shown the auxetic samples are able to sustain a maximum force which is 100% higher than the equivalent conventional fibre composites.[7] The same work also showed that the energy needed to fully extract an auxetic fibre from the resin was more than 3 times that required for the conventional fibre specimens.

We report here an investigation into the through-thickness mechanical properties of multi-component film-adhesive interface systems where the possibility of the films having auxetic functionality is considered. The predicted mechanical performance (shear modulus and Young's modulus) of a multi-component interface system containing auxetic films is compared to that of an interface containing an adhesive alone or a multi-component interface system containing conventional films.

We have previously reported the successful production of melt-extruded polypropylene (PP) films,[8,9] and so the development of adhesive-auxetic film multi-layer systems becomes a viable proposition. The use of analytical and numerical models of the type reported in this paper will serve to screen for systems showing desirable interfacial mechanical property improvements which can then be made experimentally for validation and subsequent development of improved multi-component interfacial materials.

2. Methodology

2.1 Numerical and analytical models

2.1.1 Finite Element Modelling

Three-dimensional (3D) multi-layer solid structures representing multi-component interfaces (Figures 1 and 2) were constructed using the solid brick element, SOLID45, in the ANSYS FE package, version 10.0. SOLID45 is an eight node element, with each node having 3 degrees of freedom (namely translations along the x, y, and z axes). The SOLID 45 elements representing the different layers of a multi-component interface were glued under Boolean operation in ANSYS and subsequently meshed.

In order to determine Young's modulus, the multi-layer interface (through-thickness z direction aligned horizontally) was attached to rigid plates on the left-hand and right-hand sides (Figure 1). The right-hand plate was constrained with respect to all degrees of freedom. A uniform (coupled) tensile force was applied to the left-hand plate along the z direction. The free edges of the multi-layer interface were left unconstrained to allow transverse contraction or expansion under tensile loading. The Young's modulus was calculated from stress-strain relationships in the usual manner.

Shear modulus was determined by applying a coupled shear force along the x direction of the unconstrained plate (top plate for through-thickness z direction aligned vertically in Figure 2). The maximum shear angle was determined from post analysis results from which shear modulus was then calculated. Free edges were left unconstrained.

The main assumptions in the modelling of the multi-layer film-adhesive system were as follows; (i) all materials used were linear elastic and isotropic, (ii) there existed a perfect bond between the films, the adhesive and end plates and (iii) the stiffness of the end plates was high enough to withstand deformation. The physical properties of the materials used are shown in Table 1. The films were assumed to have the same Young's modulus. The film Young's moduli and Poisson's ratios were selected to be typical of the measured values for PP films produced in previous work.[10] The end plates were given properties typical of Aluminium. The choice of adhesive Young's modulus was taken to provide systems having higher (1.7GPa) and lower (0.12GPa) values than the films, whilst remaining in the ballpark of typical polymeric adhesives. The adhesives were assumed to have a Poisson's ratio of +0.3, typical of many polymeric materials.

2.1.2 Analytical Model

Analytical predictions of the transverse tensile modulus, E_z, and shear modulus, G_{xz}, of the multi-component film/adhesive interface were obtained via the use of a modified Rule of Mixtures (RoM) approach.[11]

The analytical expressions for E_z and G_{xz} are:

$$E_z = \frac{E_{adh} E'_{film}}{V_{adh} E'_{film} + V_{film} E_{adh}} \quad [3]$$

$$G_{xz} = \frac{G_{adh} G_{film}}{V_{adh} G_{film} + V_{film} G_{adh}} \quad [4]$$

where $E'_{film} = \frac{E_{film}}{1-\nu_{film}{}^2}$, E_{adh} and E_{film} are the Young's moduli of the adhesive and film, respectively, ν_{film} is the Poisson's ratio of the film, V_{adh} and V_{film} are volume fractions of adhesive and film respectively, and G_{adh} and G_{film} are the shear moduli of the adhesive and film, respectively.

2.2 Types of multi-component interface lay-ups

2.2.1 Constant interface thickness

In this model various lay-ups were constructed to have a predetermined fixed total interface thickness of 1.0 mm. Individual film layers had a fixed thickness of 0.2 mm, typical of the thickness of melt extruded auxetic PP films.[9] The thickness of each layer of the adhesive varied from 1.0 mm (for the adhesive-only single layer interface) to 0.04 mm (for the system which contained 4 layers of films and 5 layers of adhesive - the 9-layer system). The alternating adhesive layer-film layer lay-ups are illustrated in Figure 3.

2.2.2 Progressive interface thickness (Constant layer thicknesses)

In this model, the layer thickness of the adhesive and film components were kept constant at 0.05 mm and 0.2 mm, respectively. Successive addition of adhesive and film layers resulted in a progressively thicker interface. Figure 4 is an illustration of a progressively increasing interfacial thickness of the alternating film layer-adhesive layer system, with the thickness varying from 0.05 mm (adhesive-only 1-layer system) to 1.05 mm for the system containing 4 film layers and 5 adhesive layers (the 9-layer system).

3. Results

3.1 Young's modulus

3.1.1 Low modulus adhesive

Figures 5 and 6 show comparisons of the predicted interface Young's modulus E_z of 2-phase multi-component systems containing conventional or auxetic films and the low modulus adhesive as a function of number of total layers (film plus adhesive layers) for the constant and progressive thickness models, respectively. For the constant interface thickness model (Figure 5), the FEM and RoM predictions are in reasonable agreement. The FEM predictions are slightly higher than the equivalent RoM predictions. E_z increases with increasing number of film layers. The auxetic film/adhesive interface showed the highest increase in E_z (FEM data: 31 to 290% increase for the 3-layer and 9-layer systems, respectively). This compares to an increase of 17% to 138% for the 3-layer and 9-layer systems containing conventional films, respectively.

The FEM predictions are also higher than the RoM predictions in the case of the progressive interface thickness model (Figure 6). The discrepancy is greater than that for the constant interface thickness model. An approximately constant enhancement (FEM data: 37-45%) in E_z is predicted for the conventional film/adhesive progressive interface thickness system. The auxetic film/adhesive progressive interface thickness system shows enhanced increase in E_z (76 – 117%).

Figure 7 shows the change in E_z (relative to the single-layer adhesive-only system) for low modulus 2-phase and 3-phase (i.e. containing both auxetic and conventional films) constant interface thickness systems predicted from the FEM simulations. The labelling on the x-axis corresponds to the ordering of the films (C =

conventional, A = auxetic) from the top to the bottom of the interface (see schematic inserts). Figure 7 demonstrates that the ordering of films in the 3-phase systems also influences the Young's modulus of the interface. For example, the Young's modulus of the 7-layer system containing two conventional films and one auxetic film is maximised by arranging for the auxetic film to be located in the middle of the layered structure (ΔE_z = 108% for the CAC arrangement cf ΔE_z = 100% for the CCA arrangement in Figure 7). The Young's modulus of the progressive interface thickness low modulus adhesive system was also found to depend on the relative locations of conventional and auxetic films (data not included for brevity). Clearly, the dependency on interface layered architecture is not predicted by the RoM approach which takes no account of spatial positioning of the constituents.

3.1.2 High modulus adhesive

The effect of combining films with the high modulus (1700 MPa) adhesive in a 2-phase multi-layered interface is shown in Figures 8 and 9. The FEM and RoM data show consistent trends but are once again offset from each other. For the constant interface thickness model (Figure 8), introducing the conventional films leads to a reduction in E_z with increasing number of layers (FEM data: 25 to 63% reduction for the 3-layer and 9-layer systems, respectively), whilst an approximately constant (FEM data: 7 to 12%) enhancement is observed for the auxetic film/adhesive system. The significant reduction in E_z for the conventional film systems and the minor modification in E_z for the auxetic film systems were also predicted for the progressive interface thickness model (Figure 9). The decrease in E_z occurs more rapidly for the progressive interface thickness model than the constant interface thickness model. As for the low modulus adhesive systems, the high modulus adhesive 3-phase systems were predicted in the FEM simulations to have a slight dependency of E_z on the relative locations of the conventional and auxetic films (shown in Figure 10 for the constant interface thickness 3-phase high modulus adhesive system).

The FEM model also allows other phenomena to be investigated that are not possible with the RoM approach. For example, Figure 11 shows contour plots of the Von Mises stress distribution within the high modulus adhesive constant interface thickness system for the single layer (high modulus adhesive only), and 9-layer conventional film/adhesive and auxetic film/adhesive systems. For brevity, we do not perform a detailed quantitative analysis in this paper, nor do we consider all combinations of constant interface thickness and progressive interface thickness systems. However, we include Figure 11 for consideration in the Discussion section when interpreting the Young's modulus trends presented elsewhere in this paper. It is evident from Figure 11 that the auxetic 9-layer system displays significant stress build-up in the middle of the interface relative to the other two systems.

3.2 Shear modulus

3.2.1 Low modulus adhesive

Figures 12 and 13 are plots of interface shear modulus G_{xz} versus number of layers, predicted from the FEM and RoM models, for the low modulus adhesive constant interface thickness and progressive interface thickness systems, respectively. The FEM and RoM predictions are in good agreement, with the RoM model generally tending to slightly higher shear modulus values than the FEM model. For the constant interface thickness model, the FEM model predicts shear modulus increases by 13 to 96% for the 3-layer to 9-layer conventional film/adhesive systems, respectively. The corresponding shear modulus increases predicted by the FEM model for the auxetic film/adhesive constant interface thickness system are 23 to 338% for the 3-layer to 9-layer systems, respectively.

The comparison of the enhancement in G_{xz} for a range of 2-phase and 3-phase constant thickness low modulus adhesive interfaces is shown in Figure 14. The shear modulus increase is seen to be dependent on the relative proportions of conventional and film layers, but not significantly on the ordering of the layers for a given relative proportion of layers. For example, in the 9-layer systems, the systems containing 3 auxetic films and 1 conventional film (AAAC and AACA layer ordering) have a greater increase in G_{xz} than the systems containing 2 auxetic films and 2 conventional films (ACAC and ACCA), but the shear modulus increase for AAAC equals that for AACA (ΔG_{xz} ~ 235%), and that for ACAC equals that for ACCA (ΔG_{xz} ~ 172%).

3.2.2 High modulus adhesive

Figures 15 and 16 show the shear modulus as a function of number of layers for high modulus adhesive constant thickness and progressive thickness interfacial systems, respectively. The trends of the FEM model are again reasonably well reproduced by the RoM predictions, with the RoM slightly overestimating the FEM shear modulus predictions. For the constant thickness model (Figure 15), the incorporation of conventional films with the high modulus adhesive results in a decrease in the shear modulus (by as much as 78% reduction for the 9-layer system). The auxetic film systems show enhancements in shear modulus (increasing by 84% for the 9-layer system). The enhancement for the auxetic film/high modulus adhesive system is, however, lower than that predicted for the equivalent low modulus adhesive (Figure 12).

Significant decreases and increases in shear modulus are also predicted for the conventional film and auxetic film high modulus adhesive progressive interface thickness models, respectively (Figure 16). For the progressive interface thickness systems the increase/decrease in shear modulus is effectively achieved in the 3-layer systems, with the shear modulus approximating a plateau region for systems having higher number of layers.

The increase/decrease in shear modulus of the progressive thickness 3-phase high modulus adhesive systems is dependent on the relative proportions of conventional and auxetic films (greater decrease in shear modulus for higher relative proportion of conventional films) but is relatively insensitive to ordering of films within a given relative proportion of conventional and auxetic films (e.g. ΔG_{xz} ~ -61% for the ACAC, AACC and ACCA lay ups) – Figure 17.

4. Discussion

The FEM predictions for Young's modulus are consistently slightly higher than the equivalent RoM predictions (Figures 5, 6, 8 and 9). We attribute this discrepancy to the presence of the (rigid) end plates applying a stiffening constraint on those interface layers closest to the end plates. The discrepancy is greater in the progressive interface thickness model than that for the constant interface thickness model. This is due to the overall interface thickness being lower for the progressive interface thickness model at low layer numbers (i.e. the single layer systems have thicknesses of 0.05mm and 1mm for the progressive and constant interface thickness models, respectively) and hence the stiffening (edge) effect due to the end plates is more pronounced in the thinner (progressive thickness) interface system.

The conventional and auxetic films used in the models have the same Young's modulus and film thickness, but the Poisson's ratios are extremely different (auxetic =

-0.90; conventional = +0.43). The Poisson's ratio of the adhesive is + 0.30. To understand the Young's modulus enhancements predicted for the auxetic film systems, consider the lateral expansion and contraction of the auxetic films and adhesive. As the system is loaded in tension along the *z* direction, the adhesive tends to contract laterally due to the adhesive positive Poisson's ratio and the auxetic films tend to undergo a (negative Poisson's ratio) lateral expansion. For perfectly bonded film and adhesive layers, the auxetic films therefore act on the adhesive layers (and vice versa) to oppose and counteract the lateral deformation of the adhesive. The auxetic film imposes a tensile stress on the adhesive layer in the lateral direction, and the adhesive layer imposes a compressive stress on the auxetic film in the lateral direction. Figure 11 clearly demonstrates a build up of stresses in the auxetic film/high modulus adhesive 9-layer system. For both the auxetic film and adhesive layers, the imposed lateral stresses due to the presence of adjacent layers yield a concomitant Poisson's ratio-induced reduction in the axial (z direction) displacement, thus providing a stiffening (increase) in the through-thickness Young's modulus (E_z).

In the all conventional film(s)/adhesive interface, on the other hand, the Poisson's ratio's are similar (conventional film = + 0.43, adhesive =+ 0.30) and the different transverse deformation responses of the film and adhesive components do not have as significant an effect on the overall interface stiffness. Note the absence of significant stress build up (relative to the auxetic system) for the conventional system in Figure 11. In fact the slightly larger positive Poisson's ratio for the conventional film will tend to promote increased lateral contraction of the adhesive which would lead to a reduction in the interface Young's modulus along z. For the low modulus adhesive systems containing conventional films, the enhancement in E_z is as a result of replacing a low stiffness adhesive with a stiffer film material.

The influence of adjacent layers will also contribute to the predicted slight dependency of the Young's modulus on ordering of the films (Figures 7 and 10). However a complete understanding of the ordering effect will require a more quantitative analysis not only of the effect of nearest neighbour layers but also the effects of next nearest neighbouring layers and the end effect influence of the constraining end plates.

Turning now to the predicted shear modulus trends, the shear displacement that develops for the whole interface will be the sum of shear displacements that develop in the constituent layers. Consequently, an enhanced shear modulus in the films leads to an enhanced shear modulus of the overall system, although the ordering of film layers is not likely to be as significant as is apparently the case for Young's modulus.

The shear modulus of the film/low modulus adhesive systems (relative to the shear modulus of the adhesive-only system) is increased for both the conventional and auxetic film systems (Figures 12 and 13). Noting that each layer is assumed to be isotropic in the models then, from Equation (1), we expect an increase in shear modulus of each film layer due to the film layers having higher Young's modulus than the low modulus adhesive. This dominates over any decrease in the conventional film system arising from the conventional film having a larger positive Poisson's ratio than the adhesive (the larger positive Poisson's ratio tending to reduce the conventional film shear modulus according to Equation (1)). For the auxetic film/low modulus adhesive system the negative Poisson's ratio of the film layers provides an additional very significant shear modulus enhancement for the film layers and, therefore, the overall interface. The denominator of Equation (1) dictates that if the Poisson's ratio is changed from +0.43 (conventional film) to -0.90 (auxetic film) a 14-

fold improvement in G_{film} is expected, hence the dramatic enhancement predicted for G_{xz}.

In the case of the film/high modulus adhesive systems (Figures 15 and 16), the incorporation of conventional films leads to a decrease in G_{xz}. This arises due to the fact that the film shear modulus is reduced relative to the adhesive shear modulus, both by the larger positive Poisson's ratio and lower Young's modulus of the conventional film layers. For the auxetic film/high Young's modulus adhesive systems, the enhancement due to the film negative Poisson's ratio dominates over the lower film Young's modulus and so an increase in G_{xz} is predicted, albeit proportionally lower than the equivalent auxetic film/low modulus adhesive systems.

For both the low and high modulus adhesive systems, most of the change in both the interface Young's and shear modulus occurs in going from the single-layer adhesive system to the 3-layer film-adhesive system in the progressive interface thickness model (Figures 6, 9, 13 and 16). This reflects the fact that the film volume fraction of the 3-layer progressive interface thickness model is much closer to the film volume fraction of higher layer number systems than in the constant interface thickness model. The FEM actually predicts a slight decrease in G_{xz} for the 7-layer and 9-layer auxetic film/high modulus adhesive progressive interface thickness systems (Figure 16), even though a slight increase would be expected (as predicted by the RoM) from a consideration of the higher volume fractions of auxetic film in these cases. Whilst the overall layered interface is not isotropic, we note a slight decrease in E_z at higher layer numbers is also predicted by the FEM for this system (Figure 9), and so the slight decrease in G_{xz} at high layer numbers in this case is consistent with that which would be predicted by Equation (1).

The modelling work performed in this study demonstrates how the stiffness and shear modulus of a layered interface system can be enhanced by the introduction of an auxetic constituent into the system. Interestingly, such enhancements can be achieved to significant levels even when the auxetic film is of lower modulus than the adhesive constituent. Enhancements in effective Young's modulus have been found in other systems incorporating an auxetic constituent.[12,13] Discrepancies between RoM and FEM approaches appear to be due to inter-layer interactions and edge effects which may be significant for thin interface thicknesses in particular. Layer ordering may also be desirable when designing interfaces with gradient properties to join materials in which there is a mismatch in mechanical properties; for example in joining a low modulus auxetic core material to a high modulus conventional skin material in sandwich panel constructions for aerospace and automotive applications.

4. Conclusions

Two different model lay-ups of multi-layered film/adhesive interface systems have been modelled to investigate the effect of constituent material properties, the Poisson's ratio and Young's modulus, on the through-thickness tensile modulus and shear modulus of the overall interface. It has been shown that both auxetic and conventional films affect the mechanical performance on the interface. For the specific systems considered in this work the following conclusions can be drawn:

(i) Incorporation of the conventional and auxetic film materials with the low modulus adhesive both improve the Young's modulus and shear modulus of the interface, with auxetic films showing the largest enhancements.

(ii) When the films are incorporated with the high modulus adhesive, enhancements in interface Young's modulus and shear modulus are predicted for the auxetic films, and a reduction in these mechanical properties is predicted for the conventional films.

(iii) Good agreement is achieved in the predicted through-thickness Young's modulus and shear modulus using the FEM and RoM approaches. Discrepancies can be attributed to edge effects due to end plates and low interface thicknesses, and inter-layer interactions.

(iv) The ordering of films appears to influence the Young's modulus response, but not significantly the shear modulus response.

Acknowledgements

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Tables Captions

Table 1. Properties of materials used in the models

Figure Captions

Figure 1. Tensile Young's modulus FEM model geometry.

Figure 2. Shear modulus FEM model geometry.

Figure 3. Schematics of constant interface thickness models.

Figure 4. Schematics of progressive interface thickness models.

Figure 5. Interface Young's modulus as a function of total number of film and adhesive layers within the constant interface thickness model containing the low modulus (120 MPa) adhesive.

Figure 6. Interface Young's modulus as a function of total number of film and adhesive layers within the progressive interface thickness model containing the low modulus (120 MPa) adhesive.

Figure 7. Change in interface Young's modulus as a function of layer arrangements predicted from the FEM simulations of the constant interface thickness model containing the low modulus (120 MPa) adhesive.

Figure 8. Interface Young's modulus as a function of total number of film and adhesive layers within the constant interface thickness model containing the high modulus (1700 MPa) adhesive.

Figure 9. Interface Young's modulus as a function of total number of film and adhesive layers within the progressive interface thickness model containing the high modulus (1700 MPa) adhesive.

Figure 10. Change in interface Young's modulus as a function of layer arrangements predicted from the FEM simulations of the constant interface thickness model containing the high modulus (1700 MPa) adhesive.

Figure 11. Von mises stress contour plots for the single-layer (adhesive only) and 9-layer conventional film/adhesive (CCCC) and auxetic film/adhesive (AAAA) high modulus adhesive systems subject to tensile stress applied in the through thickness direction (Young's modulus siumulations). The contours indicate Von Mises stress build-up in the auxetic system.

Figure 12. Interface shear modulus as a function of total number of film and adhesive layers within the constant interface thickness model containing the low modulus (120 MPa) adhesive.

Figure 13. Interface shear modulus as a function of total number of film and adhesive layers within the preogressive interface thickness model containing the low modulus (120 MPa) adhesive.

Figure 14. Change in interface shear modulus as a function of layer arrangements predicted from the FEM simulations of the constant interface thickness model containing the low modulus (120 MPa) adhesive.

Figure 15. Interface shear modulus as a function of total number of film and adhesive layers within the constant interface thickness model containing the high modulus (1700 MPa) adhesive.

Figure 16. Interface shear modulus as a function of total number of film and adhesive layers within the progressive interface thickness model containing the high modulus (1700 MPa) adhesive.

Figure 17. Change in interface shear modulus as a function of layer arrangements predicted from the FEM simulations of the constant interface thickness model containing the high modulus (1700 MPa) adhesive.

Table 1: Properties of materials used in the models

Material	Young's Modulus (E) (GPa)	Poisson's ratio
[a]Adhesive	1.7	0.3
[b]Adhesive	0.12	0.3
Auxetic film	0.34	-0.9
Conventional film	0.34	0.43
End plates	70	0.33

[a] 'High' modulus adhesive
[b] 'Low' modulus adhesive

Figure 1

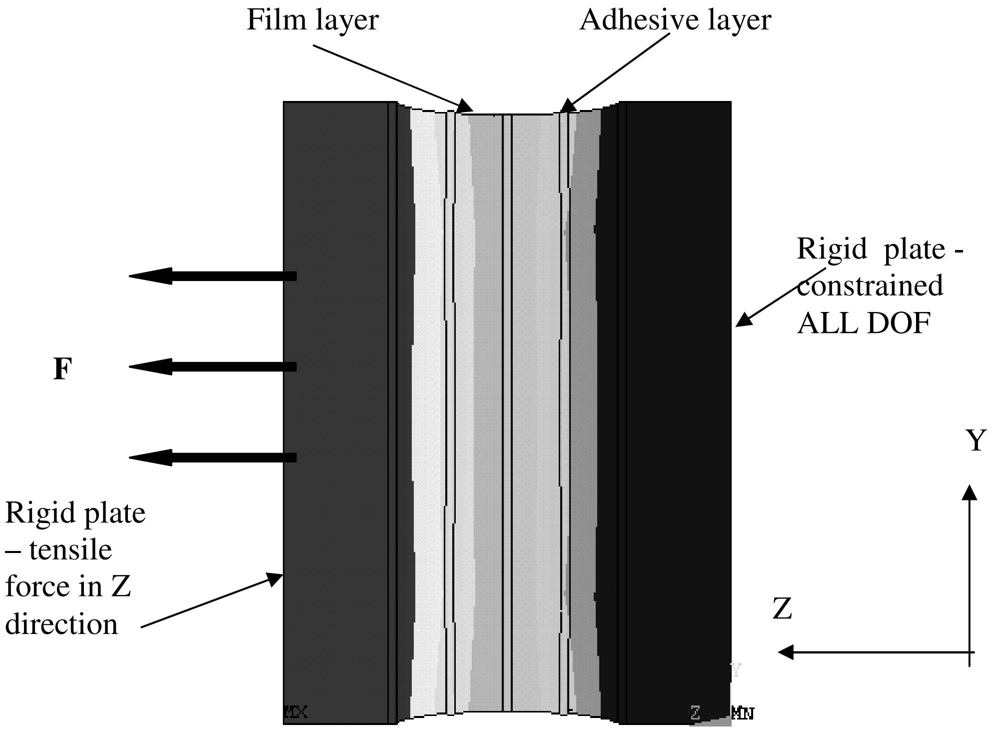

Film layer
Adhesive layer
Rigid plate - constrained ALL DOF
F
Y
Z
Rigid plate – tensile force in Z direction

Figure 2

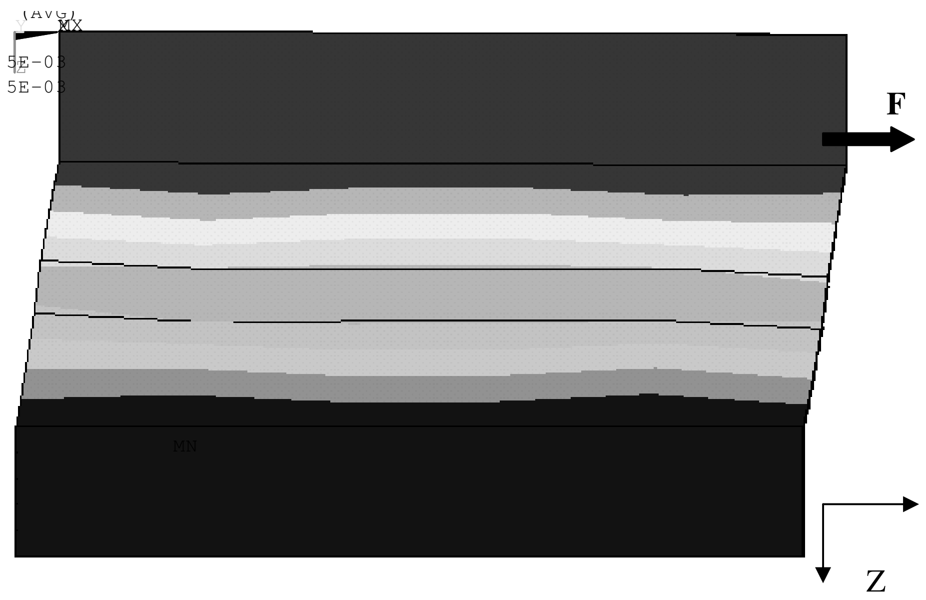


Figure 3

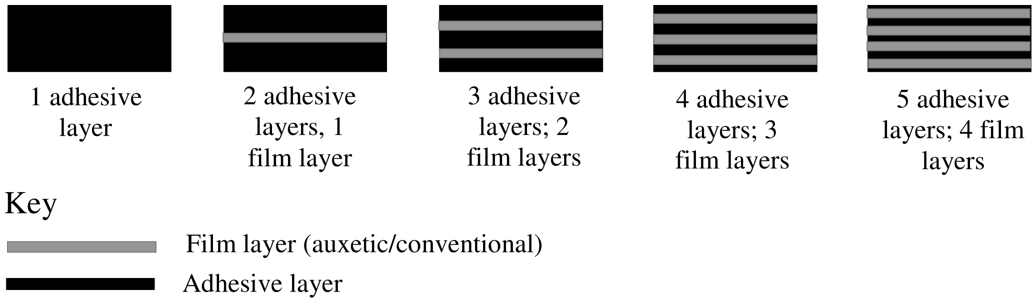

1 adhesive layer
2 adhesive layers, 1 film layer
3 adhesive layers; 2 film layers
4 adhesive layers; 3 film layers
5 adhesive layers; 4 film layers
Key
Film layer (auxetic/conventional)
Adhesive layer

Figure 4

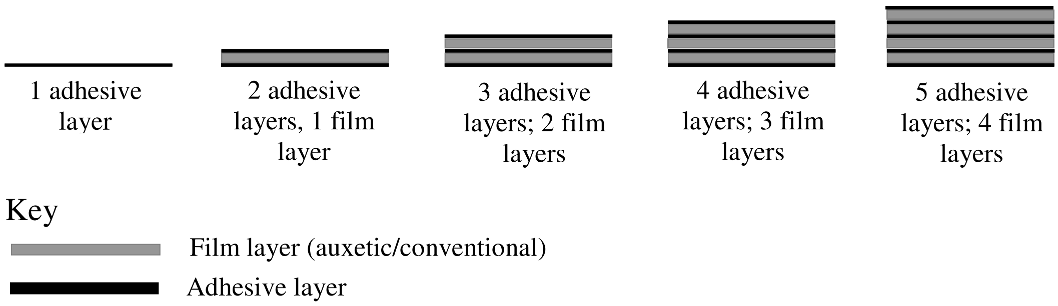
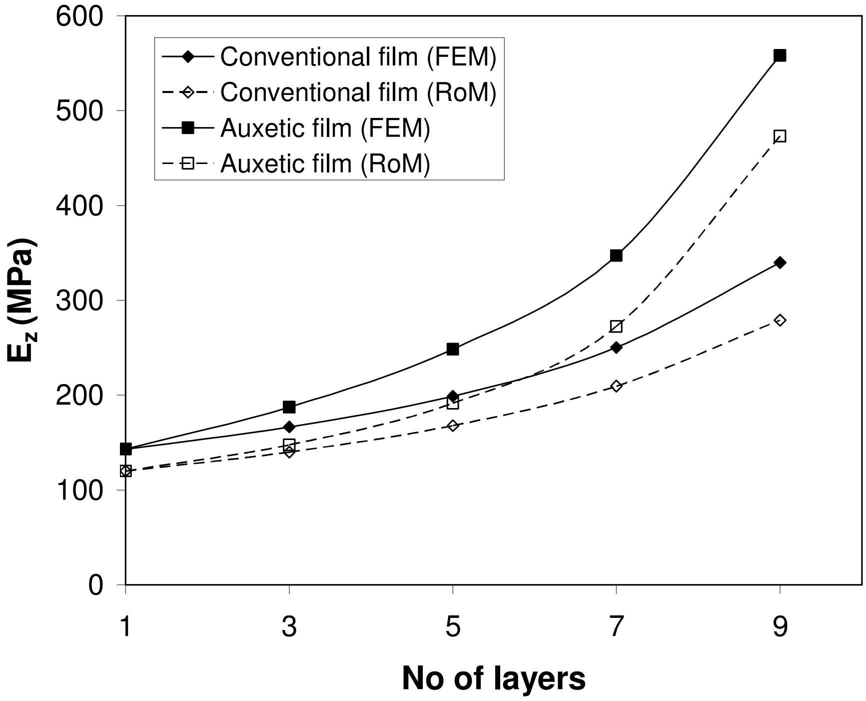
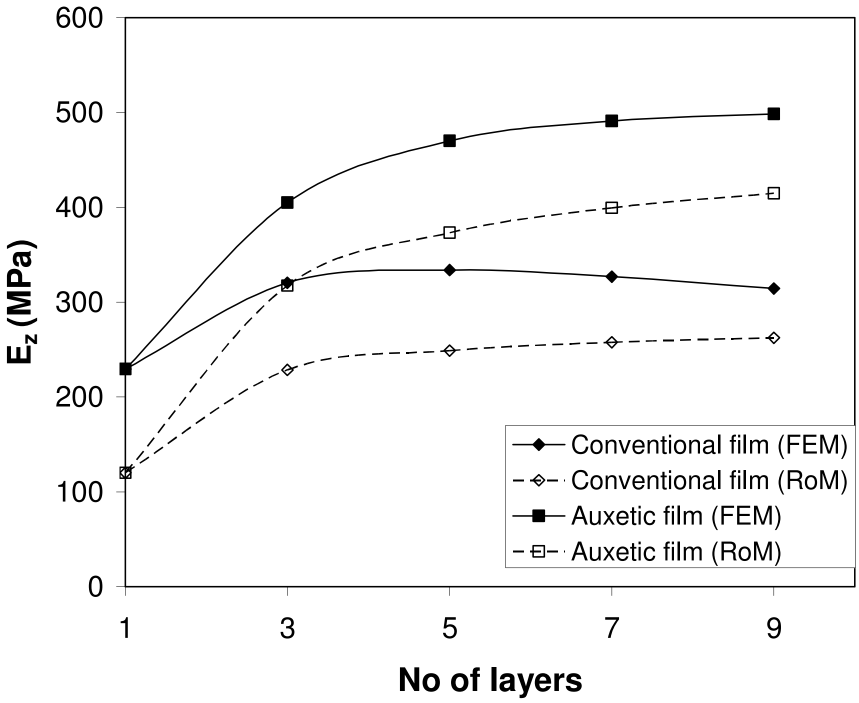

1 adhesive layer
2 adhesive layers, 1 film layer
3 adhesive layers; 2 film layers
4 adhesive layers; 3 film layers
5 adhesive layers; 4 film layers
Key
Film layer (auxetic/conventional)
Adhesive layer

Figure 5



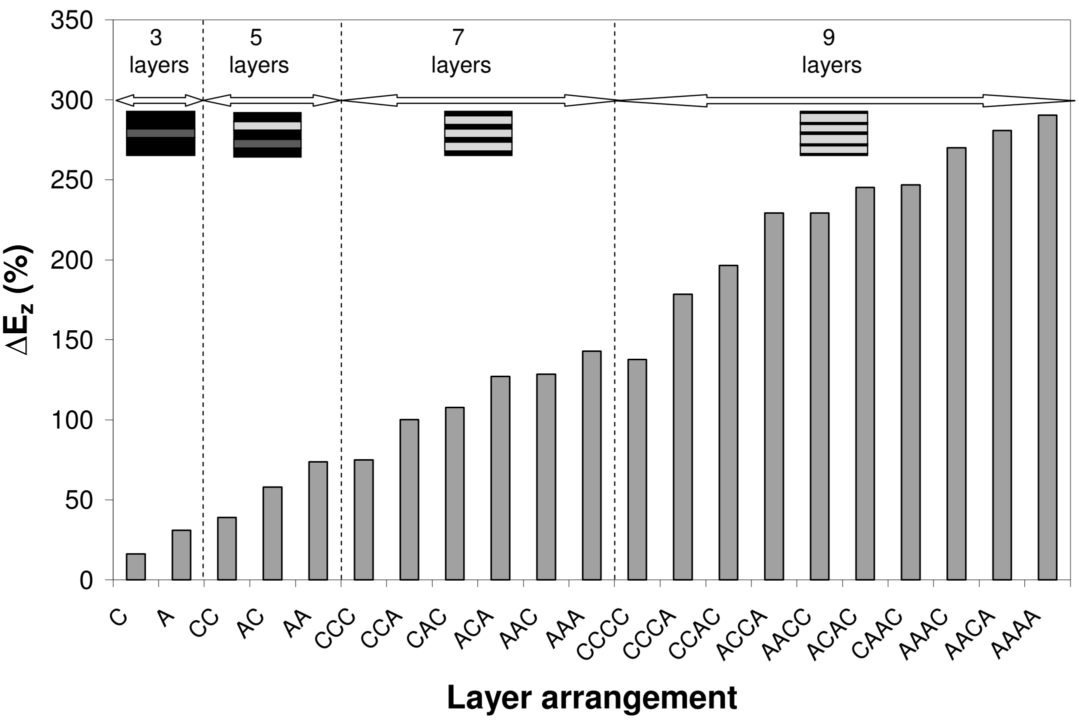
600
500
400
300
200
100
0
E_z (MPa)
Conventional film (FEM)
Conventional film (RoM)
Auxetic film (FEM)
Auxetic film (RoM)
1
3
5
7
9
No of layers

Figure 6



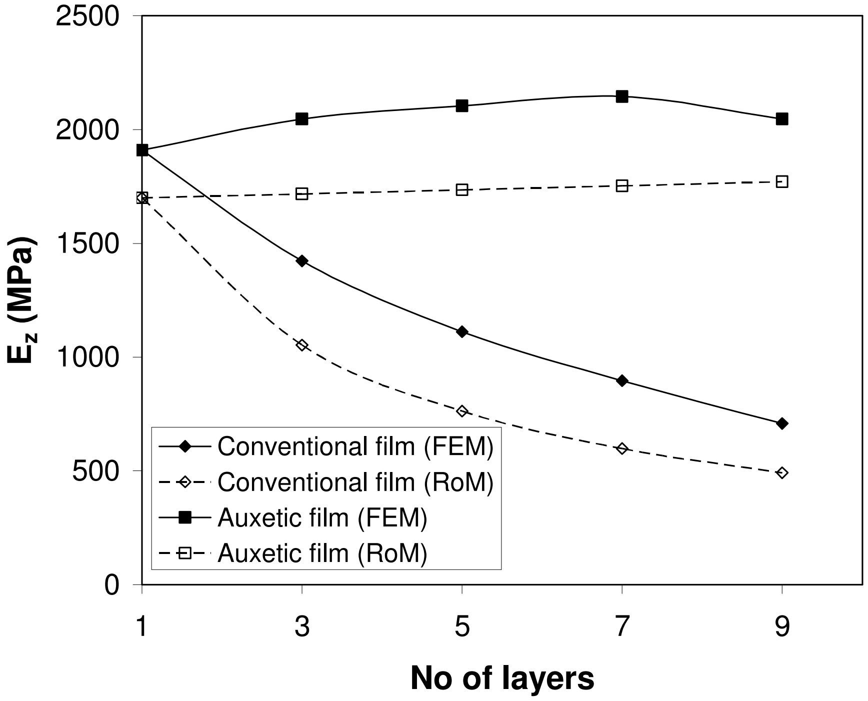
600
500
400
300
200
100
0
E_z (MPa)
1
3
5
7
9
No of layers
Conventional film (FEM)
Conventional film (RoM)
Auxetic film (FEM)
Auxetic film (RoM)

Figure 7



350
300
250
200
150
100
50
0
ΔE_z (%)
3 layers
5 layers
7 layers
9 layers
C
A
CC
AC
AA
CCC
CCA
CAC
ACA
AAC
AAA
CCCC
CCCA
CCAC
ACCA
AACC
ACAC
CAAC
AAAC
AACA
AAAA
Layer arrangement

Figure 8



2500
2000
1500
1000
500
0
E_z (MPa)
1
3
5
7
9
No of layers
Conventional film (FEM)
Conventional film (RoM)
Auxetic film (FEM)
Auxetic film (RoM)

Figure 9

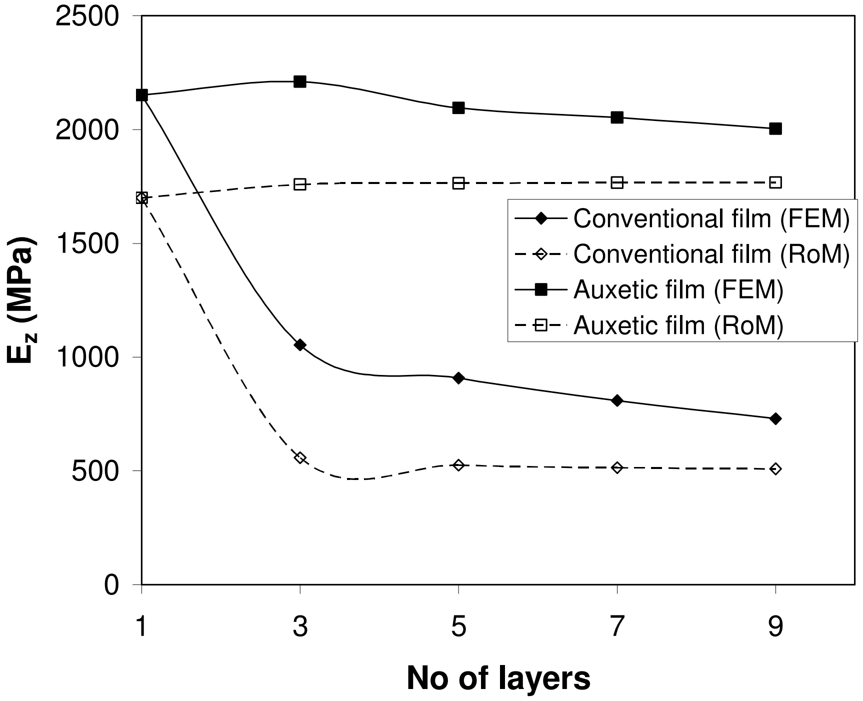

2500
2000
1500
1000
500
0
E_z (MPa)
1
3
5
7
9
No of layers
Conventional film (FEM)
Conventional film (RoM)
Auxetic film (FEM)
Auxetic film (RoM)

Figure 10

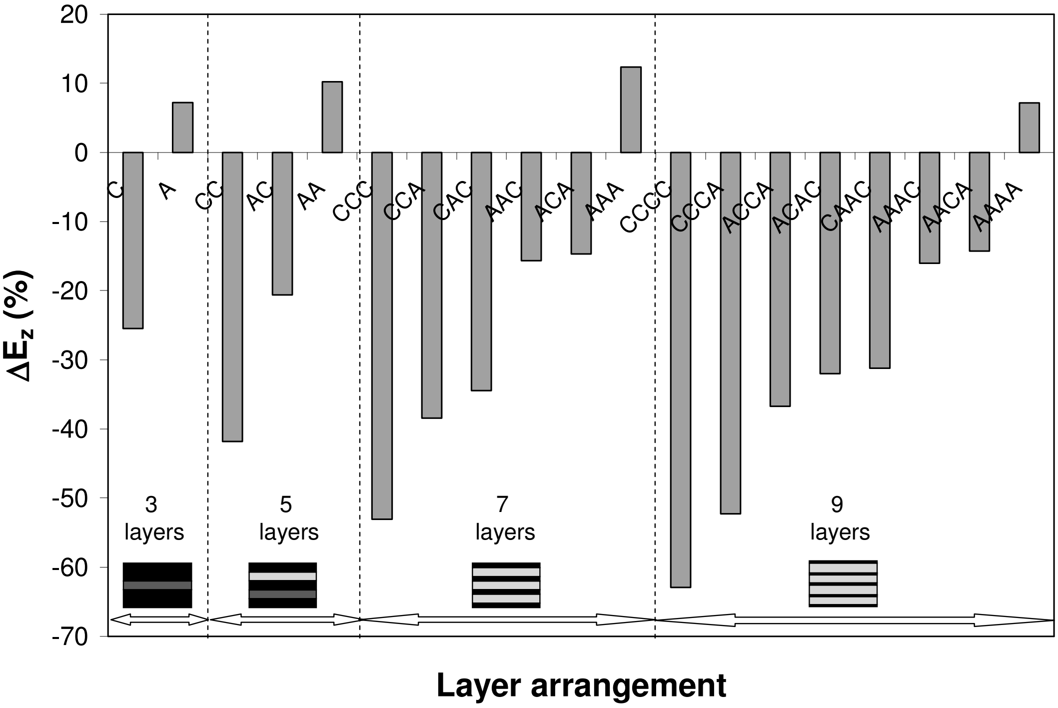
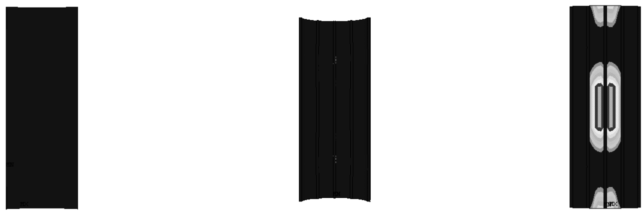
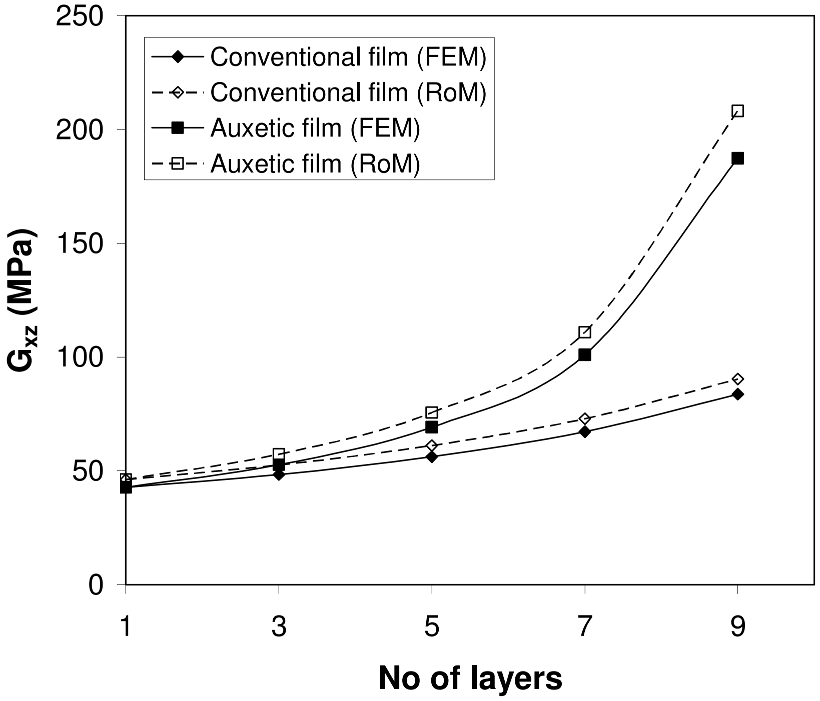

20
10
0
-10
-20
-30
-40
-50
-60
-70
ΔEz (%)
C
A
CC
AC
AA
CCC
CCA
CAC
AAC
ACA
AAA
CCCC
CCCA
ACCA
ACAC
CAAC
AAAC
AACA
AAAA
3 layers
5 layers
7 layers
9 layers
Layer arrangement

Figure 11



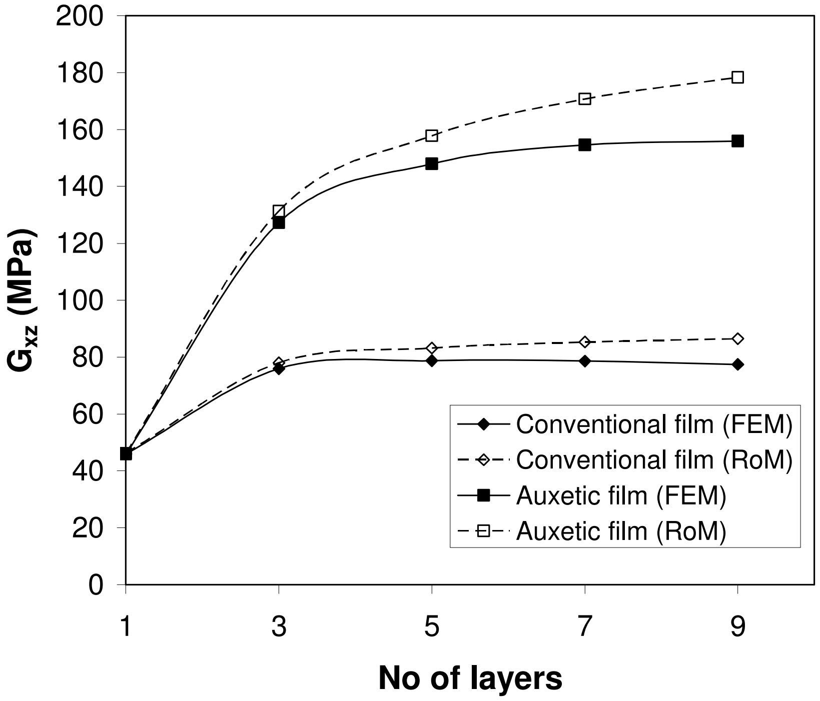
Adhesive only **CCCC** **AAAA**

Figure 12



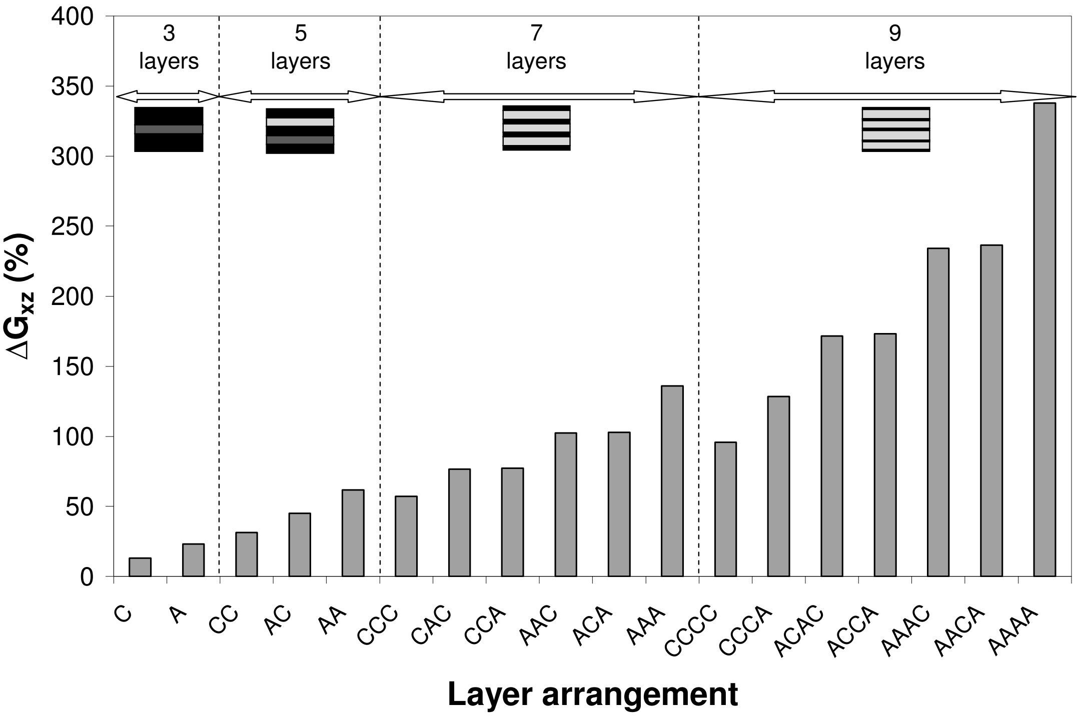
250
200
150
100
50
0
G_{xz} (MPa)
1
3
5
7
9
No of layers
Conventional film (FEM)
Conventional film (RoM)
Auxetic film (FEM)
Auxetic film (RoM)

Figure 13



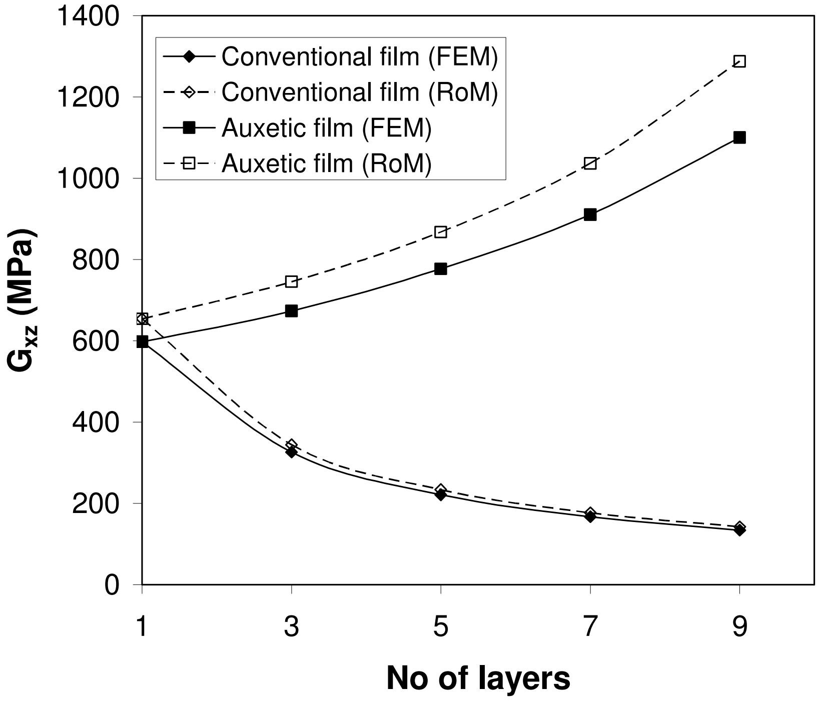
200
180
160
140
120
100
80
60
40
20
0
1
3
5
7
9
G_{xz} (MPa)
No of layers
Conventional film (FEM)
Conventional film (RoM)
Auxetic film (FEM)
Auxetic film (RoM)

Figure 14



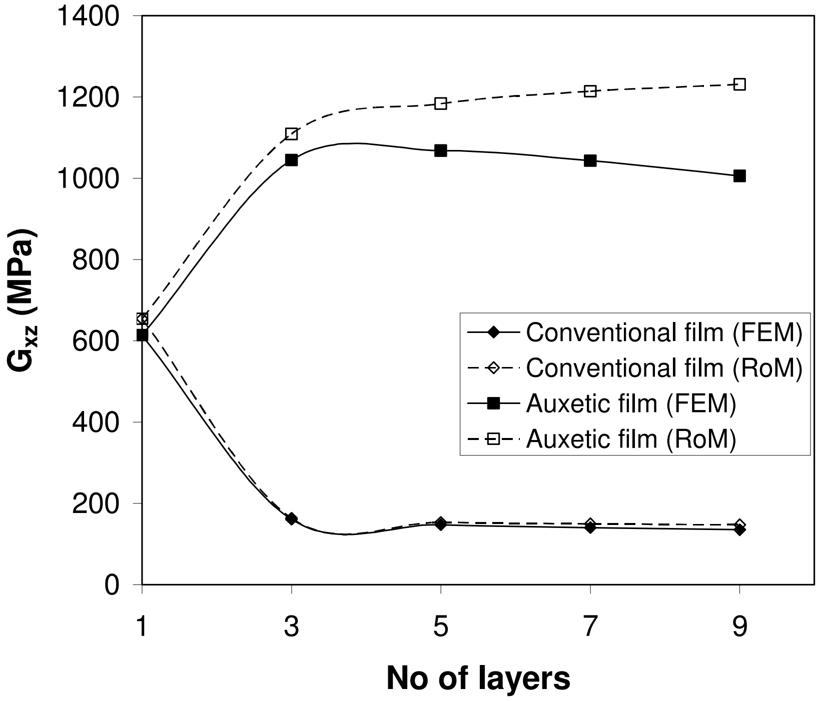
400
350
300
250
200
150
100
50
0
3 layers
5 layers
7 layers
9 layers
ΔGxz (%)
C
A
CC
AC
AA
CCC
CAC
CCA
AAC
ACA
AAA
CCCC
CCCA
ACAC
ACCA
AAAC
AACA
AAAA
Layer arrangement

Figure 15



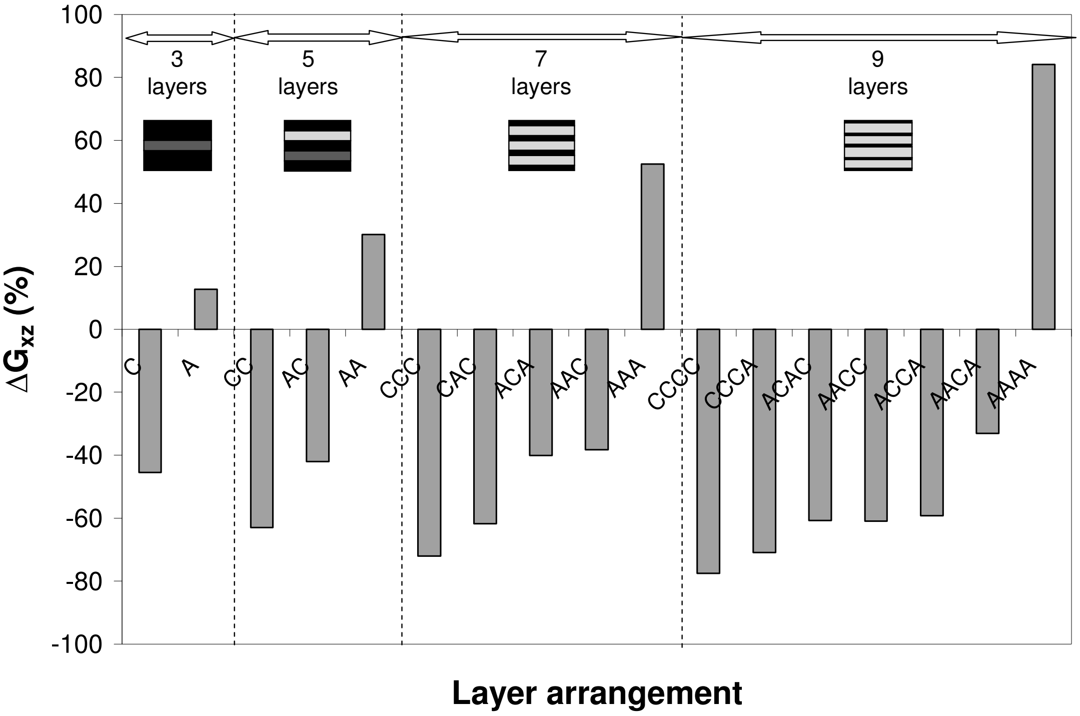
1400
1200
1000
800
600
400
200
0
1
3
5
7
9
Conventional film (FEM)
Conventional film (RoM)
Auxetic film (FEM)
Auxetic film (RoM)
G_{xz} (MPa)
No of layers

Figure 16



1400
1200
1000
800
600
400
200
0
G_{xz} (MPa)
1
3
5
7
9
No of layers
Conventional film (FEM)
Conventional film (RoM)
Auxetic film (FEM)
Auxetic film (RoM)

Figure 17



100
80
60
40
20
0
-20
-40
-60
-80
-100
3 layers
5 layers
7 layers
9 layers
C
A
CC
AC
AA
CCC
CAC
ACA
AAC
AAA
CCCC
CCCA
ACAC
AACC
ACCA
AACA
AAAA
ΔG_{xz} (%)
Layer arrangement

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